The FACETS Project

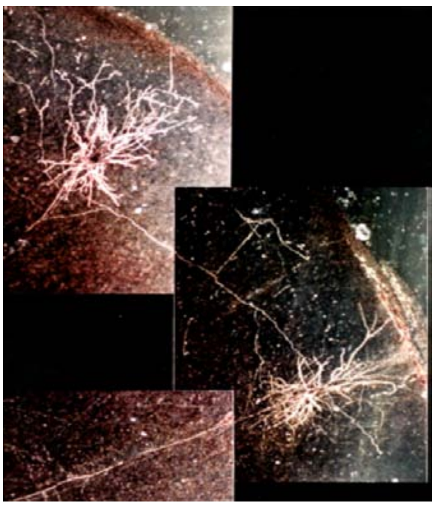
www.facets-project.org

FET Proactive

From 2005 to 2010 the European FACETS consortium carried out groundbreaking research in the areas of neurobiology, neural modelling, theory development and hardware engineering with the goal to explore the computational principles of the brain and to implement them into novel neuromorphic computing architectures. Here we provide a short overview of the main project achievements

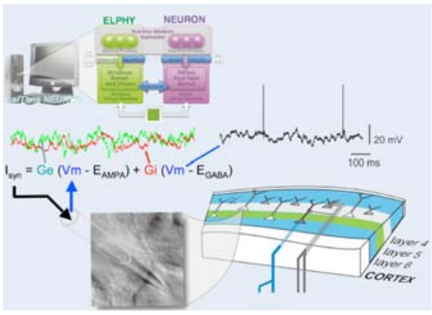
Biology

The objective of FACETS was to implement computational architectures inspired from Biology to exploit both, the mesoscopic connectivity structure of neuronal networks that underlie human-like cognition (recurrent connectivity, distributed assemblies in neocortex) and the microscopic biophysical diversity of their basic elements (neurons and synapses) necessary for multiplexing computations. Biological studies were carried out by *in-vitro* and *in-vivo* labs that are experts of sensory cortex physiology and anatomy. Comparative studies in several species (rodent and higher mammals including non-human primates) have led to a comprehensive database of sensory neocortex, with an emphasis on functional metadata related to primary visual (V1) and somatosensory (S1) cortex.



Pair of intracellularly biocytin labelled cells in cat V1 (CNRS-UNIC)

At the *in-vitro* level, the main objective was to provide single cell and connectivity data and plasticity rules to be used by computational modeling that will in turn inform novel chip design. Efforts were made to complement the existing literature by exploring synaptic connections for which still too few examples have been obtained on which to base realistic circuit models. In particular inter-laminar connections between layers 4, 5 and 6 of sensory cortex have been explored with dual intracellular recordings, biocytin-labeling of recorded neurons and morphological reconstructions.



Dynamic clamp and real-time interface between simulated neurons (Neuron) and intracellularly recorded cells in vitro and in vivo (CNRS-UNIC)

For *in-vivo* studies, three main technical achievements were obtained: 1) intracellular techniques with sharp electrodes were refined to compensate on-line for electrode resistance and improve temporal bandwidth in signal acquisition and current injection, making dynamic clamp techniques applicable *in-vivo*. 2) Intracellular labeling of single cells with biocytin was paired with optical imaging in the same animal. 3) Visual stimulation paradigms were unified between labs and unified also between sensory modalities (vision and haptic sense). For this latter purpose, an innovative multi-vibrissal matrix was developed which allows multiple parallel pixel-like stimulations of the vibrissal field and has led to center-surround and probabilistic sensory field explorations similar to those used classically for vision.

Superposition of orientation preference map obtained with optical imaging and bouton (circle) distribution of an intracellularly labelled cell in vivo (U Debrecen)

Three main biological observations were consolidated during FACETS:

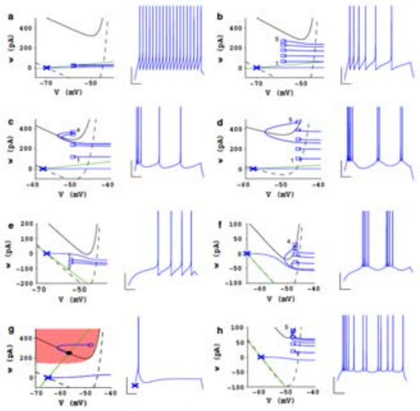
Combined functional and anatomical studies were achieved in mammals to fully reconstruct the horizontal *axonal bouton* distribution as a function of the cell type, the location of the soma in relation with the layer subdivision (vertical) and with the iso-preference orientation map concomitantly measured with optical imaging. The revealed diversity in the structure-function correlations at the single cell level suggests multiple implications of excitatory and inhibitory horizontal sub-networks in perception, to be exploited in realistic V1 models.

Visual and somatosensory cortical network dynamics adapt continuously to the statistics of incoming sensory signals: for stimuli of low dimensionality, the network architecture network is crystal-like, and composed by periodic modules of functional columns paving the cortical field. Sensory responses are dense but variable on a trial-by-trial basis, and the code requires spatial and temporal averaging. In contrast, for high dimensionality stimuli, cortical dynamics become more complex when the input statistics become closer of those linked to past experience, during development or learning, and the stimulus-locked component of the noise drops down, leading to an almost deterministic behavior of evoked membrane potential trajectories.

Mesoscopic (voltage sensitive dye imaging) and behavioral (ocular following response) measurements were compared in awake macaque monkeys. Context-dependent cortical gain functions were extracted to model these interactions and implement the role of long-range interactions in local tuning of fine grain processing in artificial systems such as the FACETS hardware.

Neural Modelling

FACETS has led to the identification of the *Adaptive Exponential Integrate-and-Fire Model* (AdEx) as a useful framework to describe neuronal activity. By adjusting the model parameters, the AdEx can explain the behaviour of many individual neurons that have been characterised experimentally. The performance of the new model has been compared with other models in an international competition that was organized in collaboration with the INCF (*International Neuroinformatics Co-ordinating Facility*).



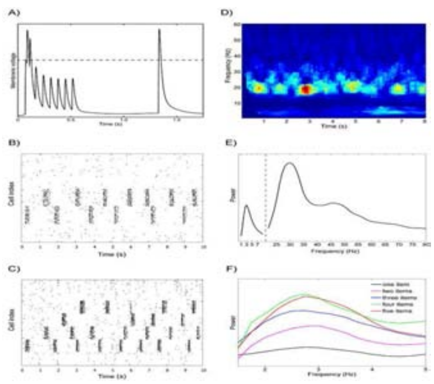
AdEx firing patterns for step current input (EPFL)

Based on the performance, the AdEx model has been selected by the consortium for a physical implementation in the stage-2 wafer based hardware system. The AdEx model is a prime example for a complete workflow in the FACETS project comprising biological measurements, numerical model testing and eventual hardware implementation.

In addition to abstract neuron models (of which AdEx is an example), the FACETS consortium has also developed a framework for phenomenological models of synaptic plasticity. The synaptic plasticity model is an extension of earlier models of Spike-Timing-Dependent-Plasticity (STDP) and takes into account recent experimental results. Both the neuron models and the synapse models are implementable in hardware and have also been used in the large-scale simulations. This part of the FACETS work is currently continued in a focused FET-open project (Brain-i-Nets), which will in turn deliver crucial input to the FACETS follow-up BrainScaleS.

At the level of network models, several independent groups performing network model simulations, from simplified models to biophysically detailed models, characterize the FACETS consortium. This constitutes an evident strength of FACETS, but also poses a serious challenge since initially all network-modelling groups used different types of models and different techniques for simulation.

FACETS has conceived a common simulation meta-language, *PyNN*, which can translate a single model description to run on different simulators, including the FACETS hardware systems. *PyNN*-based network descriptions, running both on neuronal hardware and on neuronal simulators such as *NEURON* or *NEST*, were used to extensively test the hardware. The models developed in FACETS were also used to study the genesis of *asynchronous irregular* (AI) states in networks of excitatory and inhibitory neurons. It was found that such networks can generate states which can reproduce all measurements made *in-vivo*, including multi-unit recordings and intracellular conductance estimates. Models of primary visual cortex were able to reproduce measurements made in V1, such as the dynamics of excitatory and inhibitory conductances during visual responses. Such models were also used to study the propagation of visually evoked wave activity in V1 along horizontal binding architectures and are still the subject of ongoing work.

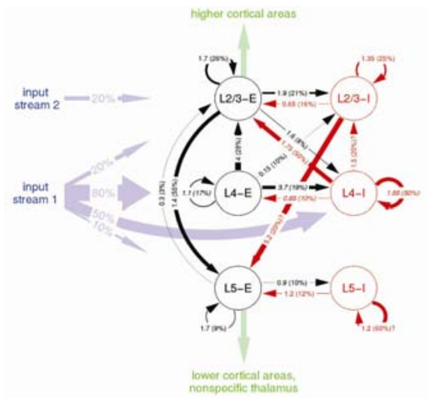


Synthetic LFP spectrogram for a network holding four items in working memory while displaying spontaneous memory reactivation. (KTH)

Finally, one of the major outcomes of the collective modelling work was to realize the need for another class of models to addressing neural systems. Most network models are based on multi-unit or intracellular recordings, but other types of measurement of electrical brain activity, such as local field potentials and voltage-sensitive dye imaging, are not used despite information-rich contents. These *mesoscopic* measurements sample the combined activity of thousands of neurons, and specific models need to be designed for these types of global measurements. Although such *mesoscopic* models were not initially planned in FACETS, the consortium re-evaluated the feasibility and usefulness of building such models. The conclusion is that modelling has to proceed simultaneously at multiple scales, including both conductance-based and spike-based variables (traditional neuronal networks) and more integrated mesoscopic variables. The BrainScaleS project will be the future platform to address these questions especially under the multi-scale aspect.

Novel Computational Paradigms

The project has identified many new mechanisms and principles that explain the structure of computations in cortical microcircuits. An example is the work by CNRS and Freiburg on the role of feed forward inhibition. A more general model for computations in cortical microcircuits, the Liquid State Machine (LSM), had been developed in a collaboration of computer scientists from Graz with a neuroscientist (Henry Markram) from EPFL. Subsequent work by the Graz group showed that the biologically most realistic version of this model, where readout neurons project feedback (axon collaterals) back into the microcircuit from which they extract information, this model has universal computational power for digital computation, thereby providing a biologically more realistic alternative to the well-known Turing machine model. In addition it was shown, that this new computational model is also universal for analogue computations, a class of computations that appears to be even more relevant for brain style computing. This new model for neural computation makes a number of concrete predictions, which can in principle be tested through biological experiments. Two of these predictions have already been confirmed by neurobiological experiments in-vivo.



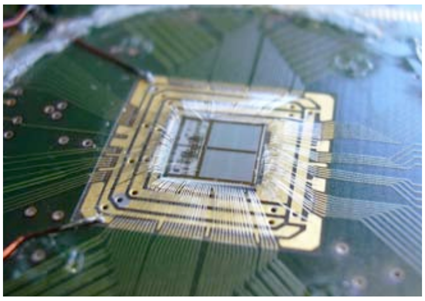
Model for generic computation in cortical microcircuits (TU Graz)

The LSM also provides a principle framework for analyzing the computational power of various concrete models for cortical microcircuits. In particular, a model for a laminar cortical microcircuit was constructed by Graz that integrates extensive anatomical and neurophysiological data from EPFL, London and Debrecen. It was shown that the resulting model for a canonical cortical microcircuit has significantly larger computational power than a generic control circuit with the same number of neurons and synapses that lacks the laminar structure of cortical microcircuits.

Generic models developed and tested in FACETS have also been customized using realistic architectures and applied to solve computational problems in vision. Te Graz group built a model for a 5 x 5 mm patch of primary visual cortex that replicates the neural dynamics in V1 of macaque, recorded *in-vivo* during stimulations with natural movies. This model replicates experimental results on computations on visual stimuli and the temporal dynamics of information about stimuli sequences observed in experimental studies. A biological realistic model of the thalamocortical circuitry of the visual pathway studied by the groups INCM and Freiburg in collaboration with UNIC provide a detailed but simple mechanistic explanation of a long standing debate of why neurons in the primary visual cortex of cat, *in-vivo*, respond with dense and variable spike timings when stimulated with artificial stimuli such as drifting gratings while they, in contrast, respond sparse and temporally precise during natural stimuli conditions. The model highlights, among other things, that cortical inhibition and thalamocortical synaptic depression are two essential neural processes for extracting a sparse and reliable representation of the visual information embedded in natural stimuli. Such model can be easily implemented using the FACETS hardware. Lastly, the KTH, INRIA, UoP and CNRS-INCM groups built large scale dynamical models that simulate high level visual tasks such as motion integration, object categorization or biological motion recognition. Some of these dynamical systems have been implemented and tested on the FACETS hardware platforms.

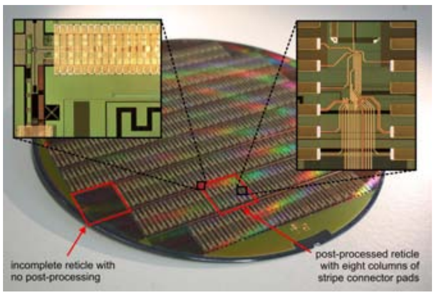
Hardware Development

Conceptually the project has followed two lines of hardware development: A real-time analogue implementation of Hodgkin-Huxley neurons with a digital realisation of plasticity and a highly configurable, general purpose computing substrate capable of implementing a wide range of user-defined massively parallel architectures even beyond the ones found in biology. The hardware systems are accessible to non-experts via the high-level description language *PyNN*, providing seamless access to the entire workflow from network definition to synthesis into the hardware substrate very much like the concept successfully developed for the classical example of Field-Programmable-Gate Arrays FPGA.



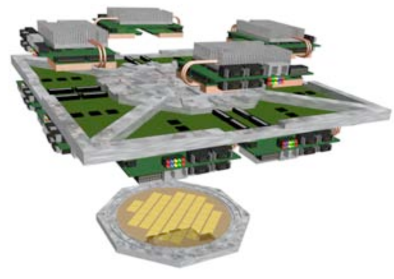
Neuromorphic chip (U Heidelberg)

In terms of technology the large-scale FACETS systems is based on a mixed-signal VLSI implementation in a standard 180nm CMOS process. Local computation in neurons and synapses is mostly performed by compact custom designed analogue circuits, which communicate via the exchange of binary action potentials (spikes) in an asynchronous fashion. The neuron and synapse models implement state-of-the-art knowledge gathered by neuroscience including plasticity mechanisms and a complex neuron model with up to 16.000 synaptic inputs per neuron, spike-frequency adaptation and various firing modes observed in biology. As the substrate represents a typical non-von Neumann system architecture the memory required for synaptic weights and cell parameters is distributed in the computing fabric and employs technologies like small SRAM cells as well as analogue floating gate units. In its final stage FACETS aimed at a wafer-based implementation of a mixed-signal artificial neural network. The project has successfully demonstrated all required technologies for such a wafer-based system.



Post-processed test wafer. Details: post processing structures (U Heidelberg).

A single wafer assembles up to 200.000 neuronal circuits and 50.000.000 plastic synapses including a freely configurable communication fabric. Within the project various technologies for wafer scale integration of neural circuits haven been developed like wafer post-processing for horizontal connections, vertical links for power distribution and external spike communication as well as an elaborate communication infrastructure for on-wafer and off-wafer spike routing.

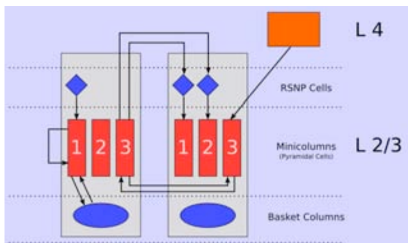


Design of a neuromorphic wafer module (U Heidelberg, TU Dresden)

The system runs in an accelerated mode exceeding the processing speed of biological real-time by a factor of 1.000 to 100.000. The corresponding time compression factor allows studying the dynamics of complex neural circuits on the scale of learning and development. A days worth of biological learning and development can be emulated in a second which means that such experiments can be repeated many times in order to systematically explore parameter spaces and network architectures.

Using Neuromorphic Hardware

The project has now entered the phase of actual neuroscientific experiments on the existing hardware and aims for the actual construction of a multi-wafer general-purpose hybrid multiscale facility (HMF) in the follow-up project BrainScaleS.



Layer 2/3 attractor model (KTH)

It is remarkable that the FACETS hardware platform has reached a wide community of users even outside the consortium. This is mostly due to the standardized PyNN based access and several public demonstrations at workshops, schools and meetings. In particular the annual Conference on Neuromorphic Engineering (CNE) in Capo Caccia (Sardinia) has served as a very effective dissemination platform. Many circuit concepts have been implemented in neuromorphic hardware including liquid-state-machines, winner-take-all architectures, synfire-chains, insect glomeruli and attractor networks. The last example is an important architecture that has emerged from the FACETS project through work carried out by the KTH Stockholm group. It implements arrays of minicolumns arranged in hypercolumns where the strongest attractor suppresses other activity and the pyramidal cells in the active attractor are in an UP-state.

The planned hybrid multiscale facility (HMF) in BrainScaleS will be a prototyping platform for parameter sets, circuits and learning rules to systematically test modelling and theories. It can then be used to design reduced and new compact circuits with specific information processing goals for potential application in everyday appliances. This workflow will be accessible to any interested researcher and represents an important ingredient to the FET-Flagship proposal "Human Brain Simulation Project (HBSP)".

Integration

The objective of the integration work was to provide tools and infrastructure to facilitate communication of results and to make results available in electronic repositories accessible to the consortium and the scientific community.

In a project such as FACETS with many groups pursuing computational modelling and other groups developing neuromorphic hardware, precise communication of computational models and simulation setups needs to be as easy and efficient as possible. An important achievement was the development of the *PyNN* common simulator interface, which enables a neuronal network model to be expressed in the Python language and then simulated, without any modifications to the code, on any of the supported simulators or on neuromorphic hardware. This has greatly facilitated communication between modelling and hardware groups, and the transfer of models from software simulation to hardware emulation. Web services, which greatly simplified access to neuromorphic hardware, were also developed.

PyNN

http://neuralensemble.org/

As well as communication of models, communication of experimental results from neurobiological experiments was central to FACETS. A *FACETS Knowledge Base (FKB)* was developed with several components, one of the largest of which is the VisionDB database, containing several thousand electrophysiological recordings and morphological reconstructions from different FACETS labs, for neurons in primary visual cortex.

Finally, major efforts have been made to share results with the wider computational neuroscience and neuroinformatics communities. Most of the tools developed in WP8 (including PyNN, NeuroTools, the Helmholtz database framework that underlies VisionDB) have been released as open-source software and have been used by and received contributions from many scientists outside FACETS. To support this dissemination and dialogue, a series of annual "CodeJam" workshops has been organised, each time bringing together 30 or so scientists from within and without FACETS for discussions, presentations and programming sessions on collaborative software development in neuroscience.

Education

The research challenges of FACETS have attracted many excellent students from different fields like biology, physics, mathematics and computer science. They have been working in an interdisciplinary and international work environment. A total of 107 PhD theses are related to the FACETS research program. In order to put the necessary and attractive interdisciplinary PhD training related to neural computation on a more sustained basis a dedicated Marie-Curie Training network has been set up.

The FACETS-ITN program will continue the successful student workshop concept developed in FACETS and make it accessible to more participants in the future.

EU-Funding

FACETS received 10.5 million € EU contribution from the 6th Research Framework Programme, FET Proactive initiative, grant no. 15879

Partners

U Heidelberg, Germany (coordinator); U Drebrecen, Hungary; IPB Bordeaux, France; TU Dresden, Germany; U Freiburg, Germany; CNRS_UNIC Gif-sur-Yvette and CNRS-INCM, Marseille, France; TU Graz, Austria; EPFL Lausanne, Switzerland; U London, UK; U Plymouth, UK; INRIA, Sophia Antipolis, France; SCCH Hagenberg, Austria; KTH Stockholm, Sweden

The Future

Brain inspired information processing carries the potential to be a disruptive technology. The FET program has been very forward looking in implementing several attractive and successful funding lines. The work started in FACETS will be carried forward by 2 new projects: The FET-open project Brain-i-Nets and the FET-proactive integrated project BrainScaleS.

Brain-i-Nets

http://www.brain-i-nets.eu

Brain-i-Nets has a research objective focused on the understanding and the artificial implementation of processes driving plasticity and learning. This project will deliver crucial knowledge needed to arrive at computing architectures able to learn and adapt to input data.

BrainScaleS

http://www.BrainScaleS.eu

BrainScaleS has a broader scope. It addresses neural computation in systems that operate in an in-vivo like state. The essential conceptual tool to achieve this objective is a multi-scale description of large-scale circuits. Multiple spatial and temporal scales will be studied in biological experiments and modelling set-ups including novel hardware architectures. The wafer-scale system prepared in FACETS will be part of a hybrid computing architecture combining neuromorphic hardware with conventional numeric computing.

On the longer run some FACETS groups together with other European researchers are actively preparing a proposal for a FET-Flagship project titled "Human Brain Simulation Project (HBSP)".

The HBSP will address brain function in a concerted way. Initially based on numerical supercomputing facilities the flagship will also pave the way and implement very large scale neuromorphic architectures which may fundamentally change the way we process and use information.

Contact

The FACETS coordinator:
Prof. Dr. Karlheinz Meier, Kirchhoff Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Im Neuenheimer Feld 227, D-69120 Heidelberg, GERMANY
E-mail: meierk@kip.uni-heidelberg.de